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Evaluation of next-generation low-power communication technology to replace GSM in IoT-applications

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Thomas G. Durand[1], Lourens Visagie[1], Marthinus J. Booysen[1] ✉
[1]Department of E&E Engineering, Stellenbosch University, Stellenbosch, South Africa
✉ *E-mail: mjbooysen@sun.ac.za*

Abstract: The large demand for smart metering and control, asset tracking, remote monitoring, and other applications has resulted in the emergence of innovative new internet of things (IoT) low-power wide-area networks (LPWANs) featuring low power consumption, low cost, high scalability and low data rate transmissions. This article compares the performance of LoRaWAN, Sigfox, and NB-IoT as emerging technologies, in terms of power consumption, throughput, scalability, and range. For practical reasons, the comparison also includes cellular GPRS. Although GPRS does not fit the description of LPWAN technologies, it is a legacy method for IoT communications and provides insight into application areas where LPWAN technology can be applied. The study gives a clear comparative overview of the advantages and shortcomings of the various communication networks and highlights the most suitable applications cases for each technology on the basis of the tested metrics.

1 Introduction

The internet of things (IoT) market is rapidly expanding due to a large demand for smart metering and control, asset tracking, remote monitoring, and several other applications to build the smart cities, farms, and industries (Industry 4.0) of the future. An IoT market outlook study conducted by Ericsson estimates that wide-area IoT networks are expected to grow from 400 million devices connected in 2016 to 2.1 billion in 2022 (70% of which will rely on cellular connections) [1]. The standard communication technology being used currently is the GPRS network because the legacy network infrastructure is already available. The devices tend to be stationary and connected to mains power, except for a few batteries or solar operated mobile devices. Other wireless communication technologies are available such as Bluetooth Low Energy (BLE), 802.15.4-based Zigbee, and WiFi, though they are typically classified as short-range networks. As the applications of IoT evolve, more focus is shifted to networks that can provide long-range communication to battery-driven devices [2].

Low-power wide-area networking (LPWAN) technologies such as Sigfox and LoRaWAN allow applications to broaden the reaches of IoT as they offer several advantages over other current communication network technologies. LPWAN technologies use robust signal modulation at low data rates to connect a network of sensors in a star topology to achieve a multi-km communication range while using less power than the current GPRS standard [3, 4]. Due to the new and evolving nature of these LPWAN technologies, this article's scope is limited to comparing only Sigfox, NB-IoT and LoRaWAN with the GPRS standard in terms of range, throughput, power consumption, and scalability.

This article provides an overview of three LPWAN technologies: NB-IoT, Sigfox, and LoRaWAN and critically evaluate them on the basis of independent comprehensive practical field testing and offers informed recommendations for applications.

Section 2 looks at related work, Section 3 provides a theoretical overview and compares the three technologies to identify the major differences between them, Section 4 describes the experimental setup and explains how the performance tests were done, and Sections 5, 6, and 7 present and discuss the results and conclude.

2 Related work

Existing studies of IoT communication standards have focused on LoRaWAN, Sigfox, and GPRS. Centenaro *et al*. [2] investigated Sigfox, LoRaWAN, and Ingenu LPWAN networks operating in the industrial, scientific, and medical (ISM) bands, taking LoRaWAN as a specific example. They concluded that LPWAN should complement current IoT standards, to enable Smart City applications as these applications can benefit from the long-range links. Raza *et al*. [5] surveyed several emerging LPWAN technologies, the standardisation activities carried out by various standards development organisations (e.g. IEEE, IETF, third Generation Partnership Project (3GPP), ETSI), and the industrial consortia built around individual LPWAN technologies (e.g. LoRa Alliance, WEIGHTLESS-SIG, DASH7 Alliance). They concluded that most standards focus on the physical and MAC layer and that further research is needed on the upper layers, such as applications, transport, and the network. Elkhodr and Shahrestani [6] investigated ZigBee, 6LoWPAN, BLE, LoRa, and the various versions of Wi-Fi, including the recent IEEE 802.11ah protocol and compared them on a theoretical level in terms of data range and rate, network size, RF channels and bandwidth (BW), and power consumption. They concluded that to enable the vision of IoT, applications need to support multiple networks to accommodate different devices with different requirements. Finnegan and Brown [7] conducted a theoretical investigation of current LPWA standards, including the primary technologies, upcoming cellular options, and remaining proprietary solutions and suggested applications. They concluded that cellular LPWAN will service devices with high QoS requirements, while unlicensed LPWAN will be used in the rest of the applications. Mekki *et al*. [8] performed a theoretical evaluation of LoraWAN, Sigfox, and NB-IoT, and found that Sigfox and LoraWAN should perform better in terms of battery, but NB-IoT was expected to deliver improved quality of service.

This study differs from other LPWAN research in directly comparing only LoRaWAN, Sigfox, NB-IoT, and GPRS. Moreover, it tests the theoretical performance of these four technologies empirically, to assess them independently and offer informed recommendations for applications for each LPWAN.

3 LPWAN overview

The two major LPWAN technologies, cellular and unlicensed band, each have advantages and limitations. LPWANs that operate in the sub-1 GHz ISM band, which consists of a few unlicensed bands, have two major advantages. The sub-1 GHz band is less congested than the 2.4 and 5 GHz bands typically used by technologies like Wi-Fi, and there is no charge for using the ISM band. However, the ISM band limits devices to a 1% time-on-air, to make the spectrum available for a large number of devices and limits the transmission power of devices to 14 dBm. This limits the devices' throughput significantly. Cellular LPWAN allows devices to transmit up to 23 dBm, with no duty-cycle limitations; however, acquiring the licensed spectrum can be costly and can take time. LPWAN networks are typically designed to connect devices with the following requirements:

• One directional (device-to-gateway) communication
• Low data throughput, typically in the order of 10 bytes per hour.
• Low power use. These IoT devices are typically battery powered, with an expected battery lifetime of ten years.
• Low cost, to enable large scale deployment.

3.1 Sigfox

Sigfox, a proprietary technology originating in France, aims to provide end-to-end LPWAN IoT connectivity. End devices use the 200 kHz variance around the 868 MHz ISM band to transmit messages via ultra narrowband (UNB) modulation (100 Hz) to base stations in a star topology at data rates varying between 100 and 600 bits per second (depending on the region). The UNB modulation results in ultra-low noise levels, which means higher receiver sensitivity, thus devices can benefit from low-power consumption and inexpensive antennas. The base station radios, which receive messages sent by devices and transmit messages to them, are deployed by Sigfox Network Operators (SqwidNet in South Africa) and connect to the Sigfox back-end through IP-based technologies such as ADSL, fibre, or LTE. Currently, SqwidNet covers most of the main centres in South Africa, with new base stations being deployed at a rapid pace. Sigfox is limited to 140, 12-byte uplink (device to gateway) messages per day per device to conform to the 1% duty cycle placed on the 868 MHz ISM band. The devices are also limited to two 8-byte downlink messages per day, which can be sent only in response to an uplink message. This prevents all the uplink messages being acknowledged by the network, thus most uplink messages follow a fire-and-forget protocol. An uplink message takes an average of six seconds time-on-air to transmit to the base stations and a 12-byte data payload is transmitted in a 26 bytes (in total) Sigfox frame [9]. The frame is transmitted three times on slightly different frequencies to ensure that duplicates exist and thus increase the chance of packet delivery. The base stations monitor all the different channels and duplicate receptions are consolidated on the back-end. The consolidated message is then displayed on the Sigfox back-end along with the receiver information (giving the user an idea of the reception quality of the device). The messages can be forwarded to the client's own data server via HTTP protocol, or a simple email service can be set up.

The scope of Sigfox's security systems is vast and cannot be covered in detail in this paper. For a comprehensive overview see Sigfox's website [10]. Sigfox ensures its security by processing the received messages and validating the message sequence counter and the device's unique symmetrical authentication key.

3.2 LoRaWAN

LoRaWAN is a network stack which uses the LoRa physical layer. It features a maximum data rate of 27 kbps and uses a star network for devices and gateways (point-to-point LoRa-based applications are also possible). LoRa uses chirp spread spectrum (CSS) modulation to transfer data from the transmitter to the receiver. CSS uses a sinusoidal signal (chirps), which has a linear variation in frequency over time, to encode data. LoRaWAN's communication range varies significantly from 2 to 5 km in urban areas to >15 km in rural areas. The range is highly dependent on the LoRa modulation settings selected.

LoRa modulation has three main parameters which can be set by the transmitter: the spreading factor (SF), the code rate (CR), and the BW. Changing these parameters changes the effective bit rate, resilience to interference, range and ease of decoding. Unlike Sigfox's random frequency selection, LoRaWAN uses specific frequencies (channels) to transmit messages.

The bit rate of a LoRa transmission can be calculated using (1), where the LoRa bitrate (R_{B}) is given in bits per second.

$$R_{\mathrm{B}} = \mathrm{SF} * \frac{4/(4+\mathrm{CR})}{2^{\mathrm{SF}}/\mathrm{BW}} \tag{1}$$

Using (1), applied to a typical LoRa application where a device uses SF = 7, BW = 250 kHz and a CR of 4/5, a physical bit rate of 11393 bps can be achieved.

There are three classes of LoRaWAN device A, B and C. In class A devices uplink consists of one uplink slot followed by two downlink slots (or windows). Class B devices follow the same rule as A, except there is an extra downlink slot. Class C devices are constantly in receive mode, switching to transmit mode only when an uplink is scheduled; however, this advantage comes at the cost of battery life.

The present study investigates LoRaWAN specifically on the Things Network (TTN). TTN is a community of users who together built a network of LoRaWAN gateways globally to establish a network for end devices to connect to [11].

Security in LoRaWAN was ensured although a unique 128-bit network session key shared between the end-device and the network server, and a unique 128-bit application session key is shared end-to-end at the application level. The combination of the two keys ensures the authentication and integrity of packets to the network server and end-to-end encryption to the application server, which prevents radio-packet sniffing. The addition of a frame counter ensures that any suspicious packets received, such as a replay attack (false messages), will be discarded if the frame count is not within expected limits, or is lower than the current frame count.

3.3 NB-IoT

Narrowband IoT (NB-IoT), also known as LTE Cat NB1, is an LPWAN supported by cellular network operators, developed to meet the new extended coverage requirements in rural and deep indoors locations set by IoT devices. NB-IoT supports a lower power IoT connection than the current GPRS standard and offers multiple years of connectivity for battery-driven IoT applications [12]. NB-IoT is supported by >30 of the world's largest mobile network operators, who provide coverage for over 3.4 billion customers and serve >90% of the IoT market worldwide [13].

In September 2015 the 3GPP announced NB-IoT as part of its Release 13, promoting the technology as the next industry general-use IoT network. NB-IoT can be rolled out on most existing network infrastructure with a firmware change (some require additional hardware), thus it eases the transition for mobile network operators and fast tracks the development of the technology. Network operators have a choice of three NB-IoT deployment options: in-band, guard-band, and stand alone. In-band deployment can be undesirable, due to capacity diversion as the 180 kHz NB-IoT spectrum is placed inside the LTE spectrum band. To solve this problem, mobile network operators can place the 180 kHz NB-IoT spectrum in the guard-bands (designed to prevent interference). NB-IoT can also be deployed in a stand-alone band if desired. This is useful when the LTE spectrum is still under development. Through multiple 3GPP releases, several frequency bands are now supported worldwide. The frequency band depends on the country and the network operator.

NB-IoT connects devices more simply and efficiently on already established mobile networks than GPRS, and is used to handle small amounts of fairly infrequent two-way data, securely and reliably. NB-IoT uses orthogonal frequency-division multiplexing (OFDM) modulation for downlink communication and single carrier-frequency division multiple access (SC-FDMA) for uplink communications and limits the BW to a single narrowband of 200 kHz. The advantage of using OFDM and SC-FDMA modulation is that a single cell (base station) can handle billions of connections and thus serve 100–200k devices [13].

Table 1 Comparison of four wide-area massive IoT networks

Technology	LoRaWAN	Sigfox	NB-IoT	GPRS
topology	star/mesh/ point-to-point	star	star	star
max data rate	27 kbps	100 bps	50 kbps UL, 60 kbps DL	115 kbps
frequency band, MHz	434/868	868	850, 900, 1800, 1900	850, 900, 1800, 1900
MCL dB	157	160	164	148
BW, kHz	125, 250, 500	0.100	192	200
modulation technique	Chirp-spread spectrum	BPSK	QPSK	GMSK
nodes per gateway	>1,000,000	>1,000,000	52,000	52,000
proprietary	physical layer	physical and MAC	full-stack	full-stack
message encryption	AES	Optional	3GPP (128–256 bit)	3GPP (128–256 bit)
deployment	early stages	commercial	early stages	commercial

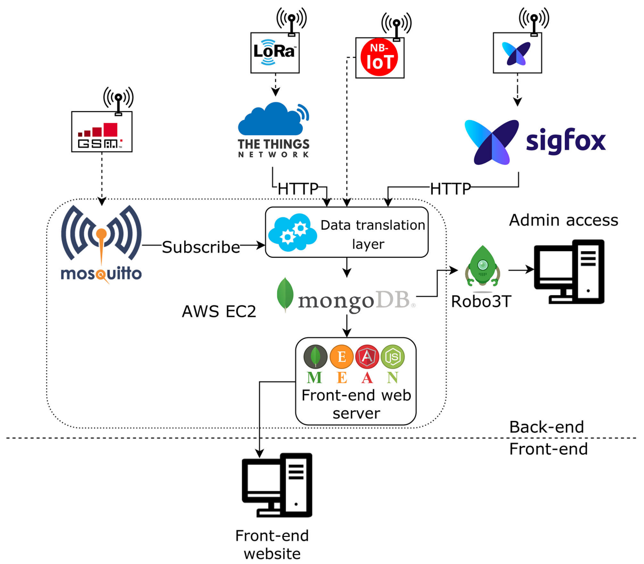

Fig. 1 *Complete system architecture overview*

Since NB-IoT uses the licensed frequency bands there are no duty cycle limitations, thus it can offer vastly greater data throughput than Sigfox and LoRaWAN. NB-IoT offers a downlink data rate between 0.5 and 200 kbps and an uplink data rate between 0.3-and 180 kbps, depending on the network conditions [13]. A further advantage of using a licensed frequency band is that there are no output power restrictions, thus devices typically transmit messages at 23 dBm (200mW). This increases the maximum coupling loss (MCL) to 164 dB, which increases coverage and penetration. This is a major advantage for IoT devices located in deep coverage situations such as manholes, underground car parks, and basements. Lastly, the high throughput that is available makes it possible to send firmware over-the-air (FoTa) updates to IoT devices. This is a common requirement in IoT devices and is not available on LoRaWAN or Sigfox networks.

NB-IoT operates in two power-saving modes (PSMs), extended discontinuous reception and PSM, which together ensures low-power operation to allow use by battery-powered IoT devices as extensively discussed in [14].

Table 1 compares the major characteristics of these four technologies, according to current research.

4 Experimental-setup

This section describes the test devices, network configuration, and back-end system that were used to measure the performance of the four IoT technologies.

4.1 Test devices

Each network test device consists of a microcontroller, a voltage regulator, a communications modem and several current measurement test points. The communications modem and the voltage vary according to the voltage and maximum current draw required. The following modems were used to test each network:

- Sigfox: WiSOL WSSFM10R1 [15]
- LoRaWAN: Microchip RN2483 [16]
- NB-IoT: Ublox Sara N200 [17]
- GPRS: Ublox Leon G100 [18]

4.2 Network setup

As both LPWAN and GPRS operate in a star network topology, they rely on a centralised gateway to collect data from nodes. The area we studied consists of 1256 km^2 of rural area, predominantly farmland, vineyards, and a central small town (Stellenbosch, South Africa) which lies in a valley.

We constructed a ‘do-it-yourself’ LoRaWAN base-station using a Raspberry Pi (which links the gateway to the back-end through an LTE connection) linked with an IMST 880A concentrator board, using a 3 dBi omnidirectional 868 MHz antenna. As Sqwidnet is the premier provider of Sigfox coverage in South Africa, we chose as our reference for the experiments a proprietary base station at the same location as the LoRaWAN base station. NB-IoT coverage is provided by a provisional test network supplied by MTN, located at the Sigfox and LoRaWAN gateway. GPRS coverage is supplied by MTN, with several base stations covering the testing area.

To demonstrate the best-case scenario for each technology, all the performance tests were done at maximum allowable transmitted power. LoRaWAN allows transmissions up to 14.1 dBm, GPRS and NB-IoT up to 23 dBm, and Sigfox up to 14 dBm. We did the LoRaWAN class A tests twice, once with SF=7, BW=125, CR=4/5, which translates into the best power consumption, and once with SF=12, BW=125, CR=4/5, which translates into the best range although it increases time-on-air and power consumption. Both end devices and gateways have the same transmission power and receiver sensitivity, so we can assume that the uplink and downlink RF performance of the various test networks should correlate.

4.3 Back-end setup

The variety and scale of data produced by our four communication technologies require centralised data gathering. Fig. 1 shows the complete system with all its components. The main aim is to store all the collected data in an always-online reliable MongoDB database hosted on an Amazon Web Services instance.

4.4 Test metrics and method

We compared our four LPWAN IoT technologies using the test metrics and procedure explained below. Table 2 summarises the procedures. Metrics evaluated empirically are indicated with an E and those evaluated theoretically with a T.

4.4.1 Maximum coupling loss.: The MCL is the loss in transmitted power that can be tolerated to still produce acceptable signal levels at the receiver. The MCL indicates the possible range that can be achieved because the free-space path loss is a function of the distance between transmitter and receiver.

We tested the MCL of the four technologies by testing their packet delivery ratio at different received signal strength indicator (RSSI) levels. We recorded the lowest RSSI for each technology that would produce a packet delivery ratio of $\geq 95\%$. We then

Table 2 Test methods used to evaluate each metric, either empirical (E) or theoretical (T).

Metric	Sigfox	LoRaWAN	NB-IoT	GPRS
MCL	E	E	E	E
power consumption	E	E	E	E
throughput	E	E	T	T
scalability	T	T	T	T

calculated the MCL as the transmitted signal power minus the RSSI limit.

As we did not know what kind antennas are used by the GPRS, NB-IoT, and Sigfox base stations, we assumed it to be a 2 dBi receiver antenna, as this is the typical value of omnidirectional antennas. We assumed transmitter and receiver losses to be 0 dB.

4.4.2 Power consumption.: In this comparison, we were interested in the power consumption of the modem and transmitter of the IoT end device only. The test devices included a microcontroller on the test board for practical reasons, but we measured only the current supplied to the modem.

We measured the current separately for the different phases of activity. The results thus include the current consumption for sleep, idle, receiving and transmitting modes, along with the duty cycle for each, assuming that each device transmits a single 12-byte message per hour and spends the rest of the time in sleep mode.

By measuring the amount of current used by the different modems, we were able to predict the expected battery life of the devices. We excluded GPRS from these tests, as GPRS's power-consumption varied drastically depending on the network conditions. To estimate the battery life we assumed an ideal 9.25 W h, 3.3 V (Sigfox and LoRaWAN) or 3.4 V (NB-IoT) battery was used. The ideal battery has no self-discharge rate, stays constant at 3.3 V/3.4 V and does not use a voltage regulator.

The information about the consumption of current and timing is based on the measured values for the modem, with no MCU power-consumption included.

4.4.3 Throughput.: 'Throughput' means the amount and rate of data that can be sent per device per time period. In this case, we were primarily interested in data sent from the IoT device to the back-end. The effective transmission rate is the rate at which payload data can be transmitted, assuming a 100% duty cycle. Such a transmission will include the actual payload data and potential overhead used for framing. LPWANs typically also enforce further constraints on data transmissions, such as the 30 s per 24 h duty cycle for TTN. The number of Sigfox transmissions from the IoT device to the base stations are also limited to only 140 12-byte messages. We thus compared throughput in terms of both effective transmission rate and the maximum amount of data that can be transmitted in a 24-hour period.

For Sigfox and LoRaWAN, we calculated the data transmission rate from the measured time-on-air. We measured the time-on-air in each case by monitoring the power consumption of the modem through an oscilloscope and measuring the time during which the modem was seen to transmit. For NB-IoT, we calculated the throughput through querying the modem statistics with the AT +NEUSTATS command.

4.4.4 Scalability.: The ease with which a network can be scaled to accommodate larger numbers of IoT devices depends on several factors, not all of them quantifiable. Various approaches are used to determine the scalability of the technologies because the medium access (MAC) layers they use vary considerably. In this study, we calculated a technology's scalability as the number of devices a base station can support.

Since NB-IoT uses OFDM and SC-FDMA modulation and GPRS is based on code-division multiple access (CDMA) technology, it was beyond the scope of our study to model or test the scalability of a base station. The scalability of an NB-IoT cell is based on theoretical research, which estimates that a single base station can support up to 55,000 end-devices per cell [19]. Similarly, the current literature estimates that GPRS technology can support up to 52,000 end-devices per base station.

Currently, LoRaWAN and Sigfox devices can transmit asynchronously, since no listen-before-talk or multiple access scheduling methods are implemented. However, these devices are duty-cycle limited, which makes their channels free for use by other end-devices, therefore enabling scalability. It is not feasible to test scalability practically, as it would take >100 sequentially transmission scheduled devices to saturate a channel (with 1% duty cycle limitation per device).

Adelantado *et al*. [20], modelled the packet delivery ratio (PDR) of a varying number of LoRaWAN packets transmitted and received per hour per node. They concluded that scalability in a LoRaWAN network is relatively low, with a PDR of 14.01% for 250 end-devices transmitting 2620 10-byte packets per hour each, and suggested implementing time-division multiple access (TDMA) in a LoRaWAN network. However, their study does not clearly define the PDR at different SFs. Bor *et al*. [21], experimented to develop models describing LoRa communication behaviour and used the models to parameterise a LoRa simulation to study scalability. They concluded that with a typical LoRaWAN setup (SF12, 125 kHz BW, CR 4/5), with each node transmitting a 20 byte packet every 1000 s and a PDR >90%, a single gateway can support 120 devices.

We could find no studies that calculate the scalability of a single Sigfox base station. According to Sigfox [21], a single base station can support 270 devices transmitting simultaneously, while ensuring a PDR of 99.9%. As Sigfox uses UNB modulation, it allows devices to transmit in 100 Hz channels uniformly distributed in its 200 KHz spectrum. This enables a huge number of devices to transmit simultaneously, without transmitting on the same frequency. The addition of three frequency diverse frames to transmit a single message further increases the scalability.

We developed a Python LoRaWAN and Sigfox simulation model to predict the number of packet errors depending on the network's density and used it to model a single LoRaWAN/Sigfox gateway supporting a varying number of up-link centric nodes.

The Sigfox base station can receive multiple packets simultaneously on different channels, so we assume that the base station does not transmit any message acknowledgments or downlink messages. Our model simulates a defined number of devices' transmissions with random transmission start-times, a constant transmission duration, and random channel selection. It calculates the number of packet collisions occurring. In any packet overlap cases, both packets are regarded as missed packets.

The simulation is adapted to model a typical LoRaWAN star network. We consider two situations, one where devices transmit a single 12 byte message every 1000 s to a single base station, and another where each device transmits a single 12 byte message sequentially to use the full 1% duty cycle. No downlink message or message acknowledgments are sent by the base station and we assume that the base station is only able to demodulate the packet with the higher RSSI level.

5 Results

This section contains the performance results for NB-IoT, LoRaWAN, Sigfox, and GPRS for each of the previously listed metrics.

5.1 Maximum coupling loss

Table 3 shows that the MCL for the four technologies correlates with the theoretical MCL shown in Table 1. It is clear that the extra overhead available in Sigfox, LoRaWAN, and NB-IoT allows for better indoor coverage than GPRS, which means that the LPWAN devices can be used in less than optimal operating conditions.

5.2 Power consumption

Fig. 2 compares the expected battery life of the three LPWAN technologies by looking at the empirically measured transmission, receive and idle times and currents of the different modems, with MCU power consumption excluded. The expected empirically

Table 3 Measured link budget of four communication technologies

	Received power limit, dB	Transmitted power, dB	Antenna gain, dB	Maximum coupling loss, dB
Sigfox	−140	14	5	159
NB-IoT	−130	23	5	158
LoRaWAN SF12	−130	14	5	149
LoRaWAN SF7	−120	14	5	139
GPRS	−100	23	5	128

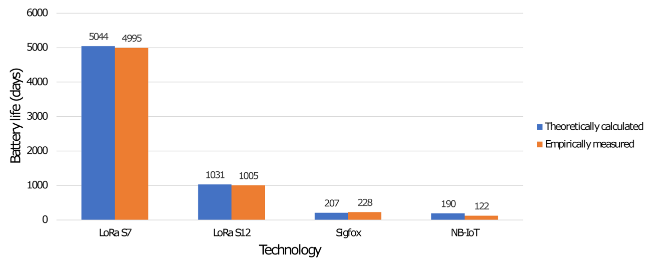

Fig. 2 *Theoretically calculated versus empirically measured battery life expectation of the three LPWAN communication technologies transmitting six 12 byte messages per hour, no MCU included*

Table 4 Power consumption calculations for three technologies transmitting a single 12 byte message once per hour

	Voltage, V	Current, mA	Power, mW	Duty cycle, %	Average power, mW
LoRaWAN SF7					
Tx	3.3	38.7	127.71	0.0616	2.19
Rx 1	3.3	13.8	45.54	0.0906	1.15
Rx 2	3.3	13.8	45.54	0.26	3.29
Idle	3.3	3	9.9	1.88	5.17
Sleep	3.3	0.00099	0.003277	3597.71	3.27
				Total:	15.07
LoRaWAN SF12					
Tx	3.3	37.8	124.74	1.48	51.28
Rx 1	3.3	13.8	45.54	0.28	3.54
Rx 2	3.3	13.8	45.54	0.28	3.54
Idle	3.3	3	9.9	1.68	4.62
Sleep	3.3	0.00099	0.003277	3596.28	3.27
				Total:	66.23
Sigfox					
Idle	3.3	2.8	9.24	6.48	16.63
Tx	3.3	56.7	187.11	2.4	124.74
Sleep	3.3	0.00100	0.003432	3591.12	3.42
				Total:	144.80
NB-IoT					
Tx	3.4	300	1020	0.0621	17.60
RRC 1	3.4	70	238	3.75	247.92
RRC 2	3.4	85	289	1.88	150.52
Idle	3.4	8	27.2	14.13	106.72
Sleep	3.4	0.00600	0.02040	3580.19	20.29
				Total:	543.04

measured battery life of LoRaWAN and Sigfox can be compared to theoretical data sheet current consumption values. The theoretical transmission time for Sigfox is based on the theoretical 100bps transmission speed. The theoretical transmission time for LoRaWAN SF7 and SF12 is based on (eq:bitrate). In the case of NB-IoT, we used our empirically measured transmission times in the theoretical datasheet calculations. We considered only the transmission time (by using the AT+NEUSTATS command), radio resource control (RRC)-idle state and deep-sleep current of the NB-IoT modem. For all NB-IoT measurements, we assumed that the device will stay in RRC-idle state for only 20 s as per data sheet as opposed to the measured 250 s.

Table 4 shows the differences in current consumption between the three LPWAN technologies for different work states: send, receive, or idle. We compared the power consumption of the technologies by looking at their total average uW power usage over an hour. LoRaWAN SF7 is the most power efficient, because of its short transmission burst, and NB-IoT is the least efficient, because of its extended RRC idle state.

5.3 Throughput

LoRaWAN supports data rates from 0.3 to 38.4 kbp depending on the SF, BW, and CD; however, as a frame consists of the actual data and a 13 byte preamble (LoRaWAN protocol) the empirical time-on-air varies. Fig. 3 shows the tested transmission times for different data packet sizes (excluding preamble). In addition to the time-on-air limitation of the ISM bands, TTN further limits the time-on-air per device, in order to ensure packet delivery. To overcome this limitation, TTN defines a fair access policy that limits the time-on-air of each end device to a maximum of 30 s per day. This is based on 86,400 s in a day, eight frequencies on which data can be received, a 5% receive duty cycle on the gateway (a minimalist stance of gateway reception time) and ensuring that 1000 nodes are supported per gateway. TTN also limits the number of downlink messages to 10 12-byte messages per 24 h, as the base station cannot receive transmissions from devices while it is transmitting.

Table 5 shows the maximum data throughput of LoRaWAN and TTN LoRaWAN per 24 h, but it is also important to adhere to the per sub-band duty-cycle limitation. We calculated the time-off a specific sub-band requires using (2)

$$T_{\text{off\_sub}} = (\text{ToA}/D_{\text{sub}}) - \text{ToA} \tag{2}$$

where $T_{\text{off\_sub}}$ is the sub-band's required off time, *ToA* is the time-on-air and D_{sub} is the sub-band's duty cycle. The time-off sub-band limitation does not limit the throughput per 24 h; however, it will limit the rate at which messages can be sent simultaneously.

Sigfox data transmissions are limited to 140 12 byte messages per day, to result in a 1% duty cycle. There is no sub-band duty-cycle limitation, thus all of the 140 12 byte messages can be transmitted sequentially with no time off sub-band required. To determine the data rate, we measured the transmission time for different frames (data + protocol overhead). Table 6 shows that the measured data rate is close to the theoretical value of 100 bps.

As NB-IoT operates in the licensed spectrum, there are no throughput restrictions, other than the data-rate restriction. We measured the uplink and downlink data rates in different signal quality environments (distances from the gateway) by querying the modem. The measured downlink rate varied from 2250 to 14,193 bps. We could find no clear correlation between the downlink data rate and the signal quality environment. This supports the claim that the throughput of NB-IoT network is network condition dependent, therefore the results may vary. The results vary dramatically from the theoretical physical layer data rate shown in Table 1, indicating that the NB-IoT network is still under development.

The throughputs for the three LPWAN technologies are compared in Table 7. The comparison is based on an end-device transmitting 12 byte messages to allow a fair comparison with Sigfox. The throughput for NB-IoT is calculated theoretically, on the basis of the best available network conditions. Table 7 shows the maximum effective data rates based on our measured data, the limitations of the technology, the maximum data that a single end-

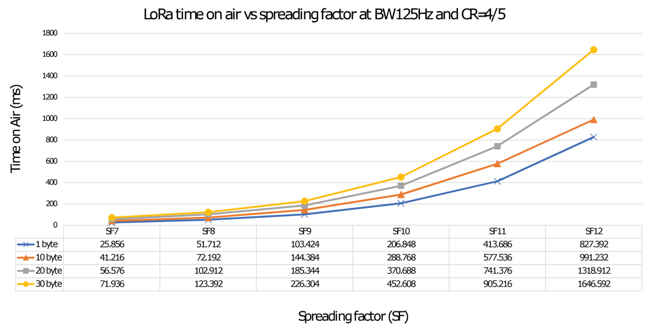

Fig. 3 *LoRa time-on-air versus SF with CD 4/5 and 125 kHz BW*

Table 5 LoRaWAN max messages per 24 h versus SF at CR=4/5 and BW=125 kHz

	Message size, bytes				
	1	6	12	20	30
LoRaWAN SF 7	18,646	16,791	14,004	12,010	9897
LoRaWAN SF 12	748	655	582	477	404
LoRaWAN (TTN) SF 7	647	583	486	417	343
LoRaWAN (TTN) SF 12	25	22	20	16	14

Table 6 Sigfox measured transmission speed

Bytes transmitted	Total frame size, bytes	Time measured, s	Data rate, bps
1	15	1.32	90.91
6	20	1.84	86.96
12	26	2.2	94.55

Table 7 Throughput comparison of the three LPWAN technologies

Technology	Maximum effective data rate, bytes/s	Network/ operator limits	Maximum payload data in 24 h, bytes	Maximum effective data rate over 24 h, incl. network limits, bytes/s
LoRaWAN TTN SF7	194.8	max time-on-air of 30 s every 24 h	5844	0.068
LoRaWAN TTN SF12	8.1	further time off sub-band restriction between messages.	243	0.003
Sigfox	5.5	maximum 140x 12 byte messages per day	1680	0.019
NB-IoT	887 – 1774	only restricted by channel data rate	168,750,000	1953.125

device can transmit in 24 h and the effective data rate of each technology over a 24 h period.

5.4 Scalability

Figs. 4*a* and *b* show that although LoRaWAN SF7 operates on only three channels, compared to the eight available channels for LoRaWAN SF12, the scalability of LoRaWAN SF7 is dramatically higher because of the short transmission bursts. This reduced time-on-air reduces the likelihood of a collision, which in turn increases scalability. Figs. 4*c* and *d* show the advantage of LoRaWAN SF12 over LoRaWAN SF7 when the time-on-air of both networks is the same. Although LoRaWAN SF7 can transmit significantly more data with the same time-on-air, the scalability is reduced because of the reduced number of channels. Although the results in this study are based on our simplified model of a LoRaWAN network with significant assumptions being made, our results correlate with those of Adelantado *et al*. [20] and Bor *et al*. [21], highlighting the lower (sub-500 devices per gateway) scalability of LoRaWAN per base station compared to NB-IoT and GPRS. This low scalability is due to the limited number of channels and the lack of any scheduling between devices. To compensate for the low scalability, an increase in spatially diverse base stations would allow packets to be received by multiple base stations at varying received power levels.

We carried out two simulations to determine the scalability of Sigfox. The first determined the maximum number of Sigfox devices transmitting a 12 byte message every 1000 s to a single base station and calculated the number of devices transmitting simultaneously. The start time of the transmission was distributed randomly. Adding more devices linearly increased the chance that two or more devices would be transmitting simultaneously. This simulation showed that with 55,000 devices transmitting the base station would reach the 270 simultaneously transmitting devices that Sigfox claims is possible while still ensuring a 99.9% PDR.

The second simulation used a varying number of devices transmitting a 12 byte message every 1000 s to a single base station. The simulation analysed any collision in time and frequency domain for each message and determined whether at least one of the three frames was correctly received. Because we had to simulate enormous numbers of devices, the computational requirements increased dramatically. This simulation, therefore, aimed only to support our first simulation. The Python simulation supported the robust scalability of the Sigfox network, as no collisions were detected for 8000 simulated devices.

6 Discussion and recommendations

Fig. 5 compares the three LPWAN technologies, on the basis of our findings from the literature review and our experimental testing and simulation. This data visualisation highlights how very differently the networks perform.

Our performance analysis of the three LPWAN technologies made it clear that there is no single IoT network solution to all IoT applications. However, certain technologies fare better in IoT applications with different MCL, power consumption, throughput, and scalability requirements.

MCL: For IoT devices used in extended coverage situations, such as deep-indoor devices or remote locations, we recommend either Sigfox or NB-IoT, as they offer a maximum MCL of more than 158 dB. IoT devices for general use would benefit from the large-scale deployment of the GPRS network, which provides excellent coverage because of its legacy infrastructure.

Power consumption: In applications where device battery life is a crucial factor we recommend, either LoRaWAN or Sigfox, because they are completely asynchronous. We found that the battery life of LoRaWAN SF 7 was five times that of LoRaWAN SF 12 and nearly 25 times that of Sigfox. This is mainly due to the extremely long time-on-air of LoRaWAN SF 12 and Sigfox. If NB-IoT worked with the mobile network operators to reduce its RRC-idle phase, it could develop a minimal power consumption to compare with that of LoRaWAN and Sigfox.

Throughput: As throughput differs greatly between the four technologies, comparisons should rather be made in either the licensed (NB-IoT and GPRS) or unlicensed (Sigfox and LoRaWAN) spectrum categories. Applications that require huge amounts of data to be transmitted, such as real-time vehicle fleet monitoring, we recommend GPRS and NB-IoT as they are not duty cycle limited. The choice of GPRS or NB-IoT will be based on the battery life requirements of the IoT device, with NB-IoT having the advantage. In the case of extremely low-throughput applications, such as water meters, power meters, and weather stations, we recommend Sigfox, as it offers a scalable solution with no base station costs involved. Although it limits the 12 byte throughput

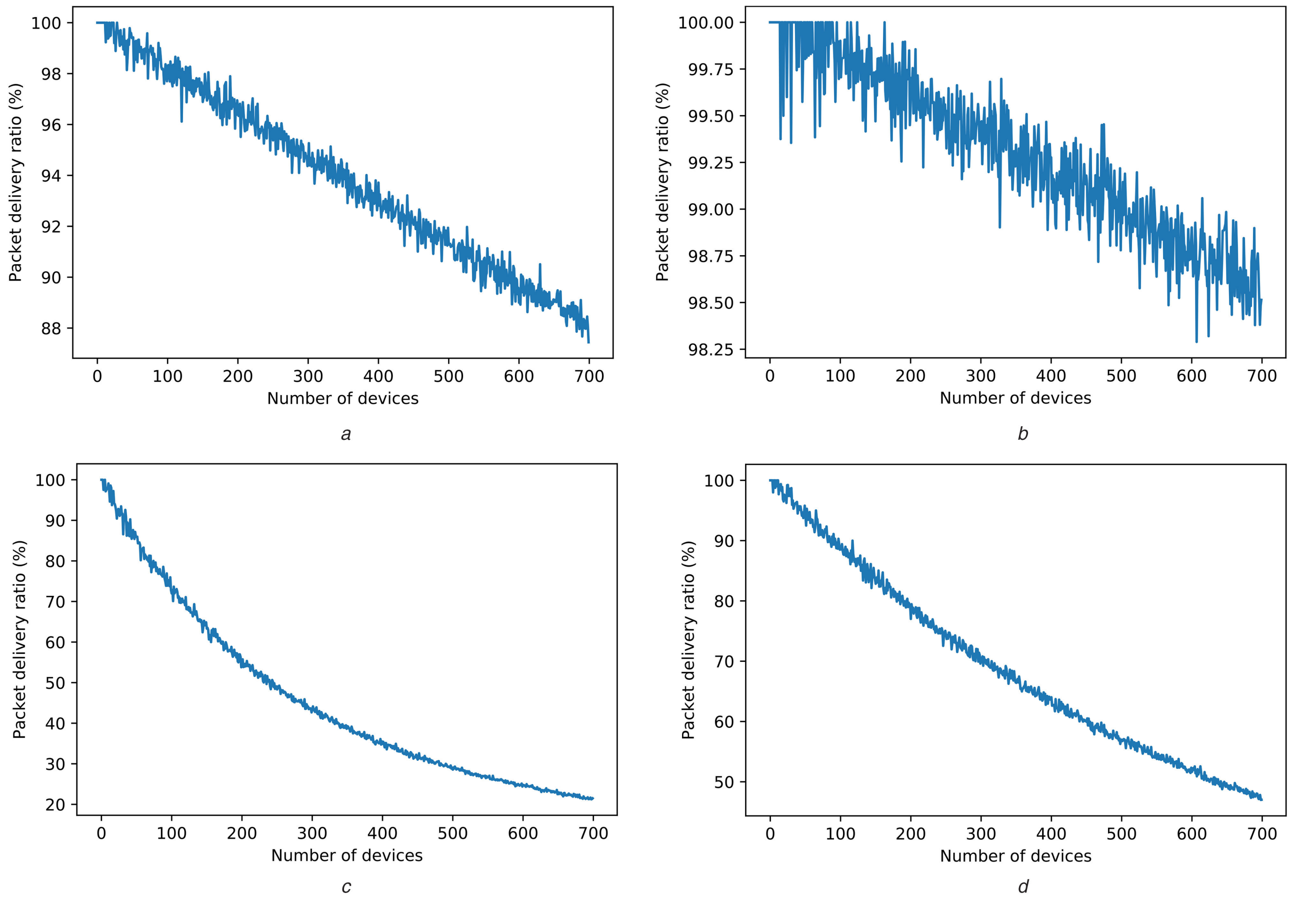

Fig. 4 *LoRaWAN SF7 and LoRaWAN SF12 packet error rates for the varying number of devices, using 12 byte messages*
(a) LoRaWAN SF7, message every 1000 s, ***(b)*** LoRaWAN SF12, message every 1000 s, ***(c)*** LoRaWAN SF7, message every 6.16 s (1% duty cycle,), ***(d)*** LoRaWAN SF12, message every 148 s (1% duty cycle)

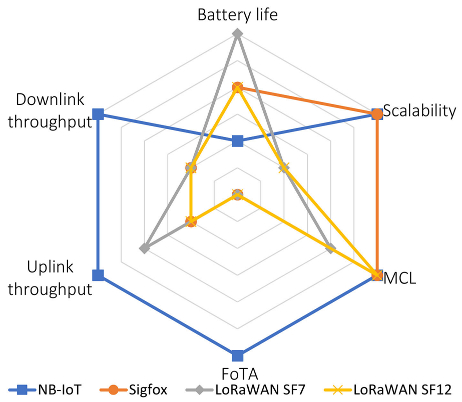

Fig. 5 *LPWAN performance summary*

per 24 h to 140 messages, this is more than the 20 messages offered by LoRaWAN SF12 (TTN).

Scalability: In deployments where large numbers of devices need to be connected, such as in smart cities, we recommend either Sigfox, NB-IoT, or GPRS, as they offer >50,000 devices from a single base station. However, if the number of spatially diverse base stations is increased, LoRaWAN will also work in a scalable deployment.

Down link latency: In applications where downlink latency is a critical component, only GPRS will suffice, as it is the only technology in this study that requires constant paging between the base station and the end device.

Down link throughput: Any applications requiring bi-directional communication of more than 120 bytes per 24 h, should use NB-IoT or GPRS, as Sigfox and LoRaWAN are limited by the duty-cycle limitations of the base station.

FoTa: GPRS and NB-IoT are able to offer FOTA upgrades to IoT devices, as Sigfox ha s limited bandwidth. This feature is supported by LoRaWAN, through the fragmentation of large payloads [22].

In summary, Table 8 shows the specifications of a typical array of IoT applications and Table 9 shows the usability of the four technologies discussed in this paper.

Table 8 IoT use requirements (high (H), medium (M), low (L))

IoT application	Uplink throughput	Downlink throughput	Battery life duration	Scalability
smart bicycle	M	L	H	L
smart parking	H	L	H	H
smart garbage bins	L	L	H	L
pet tracking	M	L	M	L
point of sale terminals	H	H	L	M
healthcare	H	H	M	H
smart agriculture	L	L	H	L
intelligent buildings	M	M	H	H
asset tracking	H	L	H	M
utility metering	H	L	H	M

7 Conclusion

Competition in the LPWAN space and regional momentum will ensure that the various technologies will continue to develop and improve to support more features and expand the network coverage. Because the technologies all have their own advantages

Table 9 IoT use applicability

IoT-application	LoRaWAN SF7	LoRaWAN SF12	Sigfox	NB-IoT	GPRS
smart bicycle	good	good	good	average	poor
smart parking	good	average	good	average	poor
smart garbage bins	good	good	good	average	poor
pet tracking	good	good	good	good	poor
point of sale terminals	poor	poor	poor	good	good
healthcare	poor	poor	poor	good	average
smart agriculture	good	good	good	average	poor
intelligent buildings	average	poor	poor	average	poor
asset tracking	good	good	good	poor	poor
utility metering	good	good	good	poor	poor

and disadvantages, it is difficult to imagine that a single one will force all the others out of the market. Rather, we expect selected uptake of each technology in specific application areas and our results show that each technology is better suited to specific applications and their concomitant requirements. Sigfox, NB-IoT, and LoraWAN SF12 performed equally well for applications where MCL (range) is paramount, with LoraWAN SF7 doing slightly worse. In applcitions where the main consideration is scalability, Sigfox, and NB-IoT substantially outperformed the LoraWAN varieties. However, if battery life is the most important consideration, LoraWAN SF7 seems to have the edge, with NB-IoT (the default setup we tested) performing worse. NB-IoT performed the best for uplink throughput, with LoraWAN SF7 coming in second. For all the other two-related metrics evaluated, namely downlink throughput and firmware upgradability, NB-IoT performs substantially better than the other technologies.

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